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CORPS OF ENGINEERS, U. S. ARMY

MISSISSIPPI RIVER COMMISSION

**CORROSION OF DRAINAGE WELLS
AT SARDIS DAM, MISSISSIPPI**



TECHNICAL MEMORANDUM NO. 3-287

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

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Aerial View of Sardis Dam, Sardis, Mississippi

PREFACE

This report is a compilation and analysis of the available information on the corrosion of drainage wells in the toe-drain system at Sardis Dam, Mississippi. It includes descriptions of the well system and the dam foundation, results of corrosion tests, water analyses, chemical analyses of some of the corrosion products, photographs of the effects of corrosion on the various types of wells used, and a discussion of the probable significance of the various factors of the environment in the corrosion process.

The investigation described herein was conducted by the Waterways Experiment Station for the President, Mississippi River Commission, during the period 1941 to 1948, with the active cooperation of the Mississippi River Commission and the Vicksburg District, CE. Personnel of the Soils Division of the Waterways Experiment Station who were actively connected with the study were Messrs. W. J. Turnbull, S. J. Johnson, W. R. Perret, and Miss Julia Bolls. This report was prepared by Mr. Perret.

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SUMMARY

A study of the results of corrosive attack on metallic and non-metallic pressure relief wells, which formed part of the toe-drain system for Sardis Dam, Mississippi, was performed for the purpose of identifying the source of the principal corrosive agents and the reasons for certain variations in the corrosive attack. The results of a number of chemical analyses and the examination of many of the corroded wells which were removed from the toe-drain system formed the basis for this study. The chemical analyses were performed on samples of water from various parts of the toe-drain system and from the reservoir, on a specimen of the lignitic clay which formed a part of the foundation, and on typical corrosion products from a brass well screen and from an iron riser pipe. All of the original wells and a group of experimental wells were removed following the installation of an enlarged system in 1946.

The data derived from the chemical analyses and the examination of the corroded wells were correlated with the soil profile of the dam foundation. The results of this correlation and analysis of the data in terms of known corrosive processes lead to conclusions that (a) the distribution of lignitic clay in the foundation exercises control over the type and intensity of the corrosion of the drainage wells; (b) the major corrosive agents were the dissolved sulfates, carbon dioxide and oxygen and anaerobic bacteria; (c) the corrosive environment was such as to promote anaerobic corrosion of the iron riser pipes, dezincification of the brass well screens and chemical attack and leaching of the cement binder of concrete well screens.

CORROSION OF DRAINAGE WELLS

AT SARDIS DAM, MISSISSIPPI

PART I: INTRODUCTION

The Corrosion Problem

1. Corrosion of the drainage wells which formed a part of the toe-drain system of Sardis Dam presented a serious problem. Sardis Dam is a flood-control structure which impounds the Tallahatchie River several miles above Batesville in northern Mississippi. It is an earth embankment consisting of an impervious hydraulic-fill core with pervious upstream and downstream shells. The soil foundation of the dam includes relatively thick pervious sand formations. The drainage well portion of the toe-drain system is required for the safe accommodation of seepage water at the downstream toe of the dam. Its operation reduces hydrostatic pressures in the vicinity of the toe and depresses the phreatic surface within the dam. Consequently, any factor which would tend to damage the well system might endanger the dam either by causing excessive hydrostatic pressures due to restricted flow into the wells or by causing piping due to disintegration of the well screens. Corrosion caused both of these types of damage to the metallic wells of the original system installed at Sardis Dam. Identification of the causative factors and processes of this damage is important to the proper design and maintenance of toe drainage facilities at Sardis Dam and at sites where similar environments exist.

Sardis Dam foundation

2. The soil profile of the foundation for Sardis Dam consists of a relatively impervious top stratum varying from 5 to 15 ft in thickness directly beneath the dam, underlain by coarse to medium sand to a depth of more than 100 ft. The sand is divided over part of the foundation area by a layer of lignitic clay of variable thickness. The top of this clay layer is at about elev 170. A profile of the foundation as shown by borings made on a line 250 ft downstream from the center line of the dam is shown in plate 1. The lignitic clay is massive beneath the north end of the dam, appears to thin out between Stations 53 and 57, and is discontinuous and possibly lenticular beyond Station 97. The clay may become continuous again in the south abutment. Between Stations 97 and 108 the dam foundation is open to underseepage throughout the full depth of the pervious material. From the north abutment to Station 97, effective underseepage is limited to the stratum of sand, averaging 35 ft in thickness, overlying the lignitic clay. The sands underlying the clay have been found to carry water at considerable artesian heads but are sealed off from the upper pervious material by the clay layer.

Drainage well systems at Sardis Dam

3. Original system. A system of drainage wells was installed in 1941 to furnish additional foundation pressure relief between Stations 111 and 82, where underseepage conditions were most critical. This system consisted of 117 wells on 25-ft centers. Each well consisted of a slotted brass wellpoint with a 1-1/2-in. galvanized wrought-iron riser pipe. The wells were placed in cased holes from which the casing was pulled. The

space around each riser pipe was sealed with a puddled backfill of silty clay. The wells were 30 ft in length with a 10- to 12-ft section of brass screen. They penetrated the pervious sands to approximately elev 190 and discharged through individual strainers into a concrete-lined collection ditch. Discharge measurements from the wells and the various other drainage facilities were made periodically.

4. Experimental well system. A group of 48 experimental wells was installed by the Waterways Experiment Station during 1942 between Stations 106+74 and 102+86. These wells were installed on 6-ft-3-in. centers between the wells of the original system on a line parallel to and 5 ft downstream from that system. A complete description of the experimental system of wells is contained in Waterways Experiment Station Technical Memorandum 195-1; "Field and Laboratory Investigation of Design Criteria for Drainage Wells." The wellpoints used in the experimental system included six types of metal screen and ten screens of nonmetallic construction. The metal screens were mostly slotted or perforated brass, but several of iron and of perforated iron pipe wrapped with brass screen wire or brass rods were included. The nonmetallic screen sections were constructed of two types of porous concrete, perforated concrete, perforated cement-asbestos, perforated steel covered with gravel bound by a plastic or asphaltic binder, perforated vitreous clay, perforated cypress wood, perforated steel pipe filled with gravel, and perforated 20-gage galvanized iron tubing. All well screens with the exception of that of well 44 were attached to iron riser pipes of from 1-1/4 to 3 in. diameter. Well 44 consisted of a perforated 10-in. pipe back-filled with a sand-gravel filter which extended to the surface. The screen sections of the

other wells were of various lengths and inside diameters. Descriptive details are presented in table 1.

Early evidence of corrosion

5. Several wellpoints of galvanized iron which were used to provide water during the construction of Sardis Dam were found to be very badly corroded after operation for only about nine months. This indicated an extremely corrosive environment.

6. Other early evidence of very corrosive conditions was found when the earth which had been placed on the spillway chute slabs to facilitate curing was removed. Some of this soil was lignitic clay from the formation into which the excavation for the spillway had penetrated. It was found that the concrete had been attacked beneath the lignitic clay cover resulting in the removal of the upper layer of mortar and exposure of the aggregate to a maximum depth of 1/8 in. Examination of the copper waterstops at this time showed that, where they were exposed to water which had leached through the lignitic clay, the copper had been vigorously attacked and had completely disintegrated in some places.

Early analyses of environment

7. Several samples of the lignitic clay and of the ground water from the immediate vicinity of the clay stratum were obtained after discovery of the attack on the copper waterstops. These samples were sent to the Rock Island District, CE, for analysis. The most significant of the tests performed on these samples was the analysis of the filtrate obtained by leaching a sample of the clay in hot distilled water. The results of this analysis are tabulated at the head of table 2. The analysis

was not as complete as might be desired, but it indicated several important factors. Most obvious of these were the extremely high sulfate content, the high iron and calcium concentration, and an absence of chloride. The process by which the filtrate was obtained produced an exaggerated concentration of the various constituents, probably much greater than in the natural ground water, but nevertheless the results were indicative of the effect of the lignitic clay on the natural water. The pH value of the filtrate was 2.7, which is abnormally acid; however, the natural pore water of the clay samples had a pH of 4.0, which is strongly acid. Ignition of an oven-dried sample of the clay showed an 8.7 per cent loss in weight, indicating that the clay may have contained an appreciable quantity of organic material.

Early corrosion tests on metal

8. The extremely corrosive nature of the lignitic clay and of the ground water at Sardis Dam indicated that special materials might be required for toe-drain facilities and similar installations. The International Nickel Co. was consulted by the Mississippi River Commission on this problem and furnished a spool composed of specimens of 12 different metals. The metal specimens were so mounted that each was completely insulated by ceramic spacers. This spool was submerged in one of the toe-drain lateral outlets in fresh seepage water emerging from the dam. The water moved over the test spool at velocities not greater than 3 ft per sec. It was not aerated and was at approximately ambient temperature. The samples were submerged for a period of 1165 days, or about 3.2 years, before removal and were then returned to the International Nickel Co. for

analysis. The results of these analyses are presented in the following tabulation wherein the materials are listed in the order of corrosion penetration.

Metal	Corrosion Rate Micro-Inches Penetration per Year
Type 304 Stainless Steel (Cr 18%, Ni 8% - Mn 2%)	100 0 100
Inconel (Ni 80%, Cr 12%, Fe 8%)	100 0 100
Nickel	200 0 1000
Cast Bronze (Cu 85%, Pb 5%, Zn 5%, Sn 5%)*	6000 0
Cu-Ni (70% - 30%)	9000 0
Monel (Ni 60%, Cu 33%, Fe 6.5%)	11000 0
Muntz Metal (Cu 60%, Zn 40%)	12000 0
Ni-Resist	14000 0
Cast Iron	34000 0
Yoloy B	37000 0
Wrought Iron	41000 0
Mild Steel**	40000 0

Note: Specimens furnished and data reported by International Nickel Co.

* One specimen of regular cast bronze was pitted to a maximum depth of 0.009 in.

** Mild Steel specimens which were 0.031 in. thick were perforated during test. The penetration given is therefore a rough estimate and might have been considerably higher. = 31000 0

9. The data contained in the above tabulation indicate that the first three metals listed were attacked at a much slower rate than the other materials. Very rapid attack occurred on the four steel and iron specimens which are grouped at the end of the table. There is no significant difference shown between these metals in this test. The metals of the intermediate group, all copper alloy metals, were attacked relatively severely, the rate averaging about 8 times that of the rate for the first group.

10. The results of these tests are of limited value to the study of the corrosion of the wells, because the test specimens were submerged in water flowing from the toe drain and were not in contact with the soil. Consequently, no quantitative correlation is possible between the rates of corrosion penetration observed in the specimens and those which were effective on the wells. However, in a qualitative sense, the tests are applicable; that is, the rate of corrosion of Inconel, stainless-steel or nickel riser pipes would probably be very much slower than that of wrought-iron pipe used. The results of this test were not available when the original well system was designed and installed. However, the immediate need for the well system was considered sufficient to make it impracticable to delay the installation until the test data were obtained.

PART II: WELL CORROSION STUDY

Removal of Wells

11. During 1944 and 1945 it became increasingly evident that the original well system was deteriorating and rapidly becoming inadequate. Discharge measurements made during 1944 indicated considerable clogging of the wells which was not completely rectified by surging the wells with compressed air. Several of the wells discharged sand and clay balls immediately following surging, which indicated partial disintegration of the screen or riser pipe. Some of the riser pipes were perforated by corrosion above the concrete lining of the collector ditch. These facts, plus the apparent need for increased capacity of the wells and an extension of the system prompted the installation during 1946 of a complete new system of perforated 6-in. I.D. redwood stave wells between Stations 122 and 67+10. After the new wells were installed, the old wells of both the original and experimental systems were pulled and the holes plugged.

Chemical Analyses

12. The very corrosive environment which evidently existed in that part of the foundation of Sardis Dam in which the drainage wells were installed indicated the need for a careful study of the corrosive elements in order that the new system might be fabricated of materials which would have a longer useful life than the original wells. To accomplish this purpose, two series of water analyses were performed which included numerous samples from the well system. The first of these analyses was

performed by the Waterways Experiment Station and the second by the Barrow-Agee Laboratories at Memphis, Tenn., in cooperation with Mr. Dudley K. French, consulting chemist.

Waterways Experiment Station water analyses

13. Samples for the water analyses performed at the Waterways Experiment Station were obtained during March 1945. A total of 18 half-gallon samples were procured, of which 12 were taken from wells of the original system at intervals along its length; one was from a piezometer, and five were from toe-drain laterals at various points between Stations 42 and 102. These samples were taken in clean glass containers which were thoroughly flushed out several times with water from the pertinent well prior to filling. The results of tests performed in analyzing the samples are presented in table 2 as the "W" series. Facilities for determining the dissolved oxygen, carbon dioxide and hydrogen sulfide contents were not available when the samples were obtained, so information on these characteristics is missing. The significance of the results of these analyses as well as of the Barrow-Agee tests is discussed in a later section of this report.

Barrow-Agee water analyses

14. Two sets of water samples from Sardis Dam were tested by the Barrow-Agee Laboratories during the spring of 1945. The first set consisted of two samples; one from the reservoir, the other from well 5 at Station 110+05 of the original system. The data obtained from these samples were not completely reliable because of difficulties with the initial tests and insufficient quantities for the performance of duplicate

analyses. These tests were made early in April 1945. The second group obtained during June 1945 consisted of 12 samples, of which 4 were taken from wells 9, 21, 37 and 86; 4 from toe-drain laterals in the vicinity of each of these wells, and 4 from the reservoir. Of the latter, two (BA-13 and BA-14) were taken from a point 2 ft above the bottom, and two (BA-15 and BA-16) were taken 2 ft below the reservoir surface. The location of these samples and the method of analysis were specified by the consulting chemist, Mr. French, to whom the results of the analysis were submitted for interpretation. The tests consisted of determination of pH values, free carbon dioxide content, and soap hardness for all well and toe-drain samples. Two composite samples were made, one (BA-11) of the four well samples (BA-3 through BA-6), the other (BA-12) of the 4 toe-drain samples (BA-7 through BA-10). A more complete analysis was performed on each composite sample. Fairly complete analyses were made on each reservoir sample. No dissolved oxygen tests were made on any of these samples and total alkalinities and total acidities were not determined. Some of the water samples which were left stoppered for several days showed growth of algae. These algae were reported to be of the type which reduces oxides by production of hydrogen. The results of these tests are included in table 2 as the "BA" series. Their significance will be discussed in a later paragraph.

Examination of Wells after Removal

15. The removal of all wells of both the original and experimental systems following installation of the new wooden well system afforded an opportunity for close study of the results of corrosion on the various

materials included in the two systems. All recovered portions of the screen and riser pipe sections of the wells were examined and pertinent features of some were photographed. Portions of the corrosion products from the wrought-iron riser pipes and parts of two of the brass well screens were also analyzed chemically.

16. The wells of the original system were found to have been corroded differently in different parts of the system. The well screens near the south end of the system (plate 1) were heavily attacked, while the riser pipes suffered only minor corrosion. In the central portion of the system, corrosion of the wells was of only minor importance, the mild attack being generally distributed over both screens and riser pipes. Near the north end of the system the well screens suffered only superficial attack, but the wrought-iron riser pipes were corroded internally and externally. The external corrosion, which was the more vigorous, was characterized by deep pitting and had disintegrated the pipe in many of the wells. The screen sections of the wells of the experimental system were more vigorously attacked than were the riser pipes. This system was located within the south portion of the original system. Of the metal portions of this system only the galvanized steel sheet riser sections of wells 46, 47, and 48 were perforated by corrosion. However, most of the screen sections of the wells in the experimental system suffered from corrosion in varying degree.

17. Photographs of plates 2 through 9 show the various types of wells in the experimental system prior to installation, typical wells of this system after removal, and wells from various parts of the original well system.

18. The photographs of plate 3 give a general indication of the corrosion which occurred in the brass and combined brass and steel well screens of the experimental system. Wells 1 and 3 of this system had screen sections which consisted of a perforated iron pipe core on which a tight helix of brass rod of trapezoidal cross section was wound over longitudinal spacers. Deposition of corrosion products on these well screens apparently restricted the openings critically. The screen of perforated brass on well 6 showed very little corrosion. The screen of well 7 was very badly clogged with incrustation and corrosion products, although there was no evidence of serious disintegration. The slotted brass screens of wells 15 and 16 showed a rough surface, which was found to be typical of the corrosion of brass at the south end of the original system, and some obstruction was evident in the finer slots in well 16. The screen of well 19, which consisted of a perforated iron pipe core on which brass screen and perforated sheet brass were wrapped, showed considerable incrustation. The deterioration of this well screen, which is evident in the photograph, may be in part due to the removal operations. The screens made of perforated iron pipe wrapped with fine-mesh brass screen, which were used in wells 25 and 27, showed considerable corrosion of the screen mesh, and incrustation and obstruction of the perforations in the core pipe were severe. Several well screens of the types which were included in plate 3 and described above were dissected on a diameter and are shown in section in plate 5.

19. The effects of exposure of nonmetallic well screens to the corrosive water of the Sardis Dam toe-drain system are illustrated by the photographs of the screen sections of wells 38 through 43 of the

experimental well system on plate 4. The porous concrete in both well 38 and well 41 disintegrated badly. Although some damage probably occurred during removal of the wells, a close examination of the remaining fragments indicated that chemical attack and leaching probably removed much of the cement and weakened the structure critically. The photographs indicate that the porous pipe of well 41 had either disintegrated or was lost nearly completely during removal and that only the nonporous joints of the porous concrete pipe of well 38 remained essentially undamaged in the screen section. The perforated square cypress screen of well 39 and the perforated vitreous clay pipe screen section of well 43 showed less damage than any other used in the experimental system. The gravel-pack well screen of well 40 showed considerable incrustation. Most of the gravel of this well screen was lost as a result of destruction of the cement binder by chemical attack and leaching. The perforated concrete pipe screen section of well 42 remained serviceable. However, the removal of an appreciable quantity of the cement by leaching and chemical attack exposed the aggregate and if continued at the same rate would have rendered the pipe unserviceable in a relatively short time due to enlargement of the perforations and weakening of the pipe walls.

20. The incrustation and corrosion in the interior of the screens of wells 1, 3 and 27 are shown in the photographs of the dissected screens on plate 5. There is evidence of corrosion of the iron pipe cores of both types of screen with no indication of deterioration of the brass screening. Incrustation within the core and between the core and screen was heavy and interfered with flow into the well. Corrosion in these well points was evidently uniform with no indication of pitting or structural weakness.

The heavy incrustation is composed of iron salts and some fine-grained soil which invaded the well. These deposits nearly closed the perforations and occupied over half of the cross section of the core.

21. A portion of the slotted brass well screen from well 33 dissected on a diameter is shown in plate 6. There is evidence of some incrustation and deposition of fine-grained soil particles on the interior of this well screen. The important feature of the picture is, however, the evidence of disintegration of the slotted well screen in the vicinity of its connection to the threaded bronze pipe nipple by means of which it was connected to the riser pipe. This condition was relatively common in the wells toward the south (low-numbered) end of the experimental well system. A dissected portion of the cement-asbestos well screen and metal riser pipe coupling of well 37 is also shown on plate 6. This well screen was sheared off less than 1 ft below the coupling during removal from the ground. The break occurred along a circumferential row of perforations which formed a weak zone. There is no evidence of appreciable chemical attack on the recovered portion of the well screen, although some slight attack may be indicated by the presence of asbestos fibres which have been freed from the cement matrix. The interior of this screen was free of incrustation, but showed iron stains. The roughness which is evident in the photograph of the interior is due to chips forced out by the drill during perforation of the cement-asbestos pipe.

22. Several of the destructive effects of corrosion are emphasized by the close-up views shown in the photographs of plate 7. In the photograph of the slotted brass screen from well 19 the weak, brittle condition of the brass is exaggerated by damage done during dissection. However,

the difference between the condition of this screen and that of the similarly dissected one from well 33 shown in plate 6 indicates the definite loss of strength by the former. The photograph of the details of the porous concrete pipe screen of well 38 illustrates the complete disintegration which occurred. The chemical attack and leaching of the cement from the perforated concrete section of well 42 are emphasized by the exposure of the aggregate shown in the third photograph of plate 7. The final photograph of this plate illustrates the complete corrosive destruction of the recovered portion of the 20-gage galvanized sheet steel section of well 48 of the experimental system.

23. Corrosion of typical wells from the original well system is illustrated by the photographs of plate 8. The strainer caps which were placed at the top of each well to prevent the entrance of foreign bodies which might obstruct the well were galvanized cast iron. These caps, illustrated in the first photograph of this plate, showed very heavy corrosive attack in the portions which were subject to flow of the well water, but were evidently undamaged over that portion which was exposed only to the atmosphere. The corrosion of these strainer caps was uniform with no indication of pitting. The type of corrosion which was found to be characteristic of the extreme south end of the well system is illustrated by the photograph of well 3 (original well system) at Station 110+55. The brass of the well screen had a characteristic rough surface, was brittle and most of the slots were enlarged. The galvanized wrought-iron riser pipe showed little damage from corrosive action, the zinc coating was still present over much of its surface and the interior of the pipe was covered with only a thin uniform incrustation. Some minor

corrosive pitting was evident on the riser pipe in the vicinity of the screen coupling. The photograph of a portion of well 58 at Station 96+80 illustrates the type of corrosive action which was general in the central portion of the original well system. Neither the brass screen nor the galvanized riser pipe shows evidence of serious corrosion. The riser pipes of the wells in this part of the system showed some evidence of corrosion directly below the ground surface, but this had not progressed to a serious degree when the wells were removed. The photograph of well 104 at Station 85+27 shows typical results of corrosive action on the wells at the north end of the system. The brass well screen was incrustated near the riser pipe joint, but otherwise showed no detrimental effects of corrosion. The riser pipe, however, had been subjected to extremely heavy corrosive attack. This attack was heaviest near the brass screen and directly below the ground surface. The corrosion showed that very extensive pitting occurred; many of the riser pipes of wells in this vicinity were perforated to the extent of nearly complete disintegration.

24. A general view of part of well 106 from the north end of the original system at Station 84+75 and details of a section of the perforated riser pipe from that well are shown in plate 9. The nature of the perforation and of the interior incrustation is shown in the photographs. The perforations appear to have resulted almost entirely from pitting of the outer surface of the pipe. Corrosion of the interior of the riser pipe appears to be uniform and to involve incrustation to a thickness of about $1/8$ in. A portion of the multilayer incrustation which also occurred on the outer surface of the riser pipes in some places is also shown on plate 9.

Analysis of Corrosion Products

25. Qualitative chemical analyses were performed on several specimens of the incrustation from the interior and exterior of riser pipes from various portions of the original well system. These analyses were directed toward determination of the acid radical -- sulfate, carbonate or chloride -- which might indicate the predominant reaction in the corrosion process. Samples from the interiors of wells 31, 90 and 115, at Stations 103+55, 88+80 and 82+50 respectively, all showed a marked preponderance of sulfate, with moderate amounts of carbonates in wells 90 and 115, a trace of carbonate in well 31, and only traces of chloride in the material from all three wells. A specimen of the exterior incrustation from well 115 was found to have a distinctly layered structure, four layers being evident in the specimen tested. Each of these layers was sampled and analyzed. For convenience of reference the layers are designated by number, layer one of the sample being nearest the metal and layer four nearest the soil. Only layer one contained carbonate and this was in moderate amount. Chlorides were found as a trace only in the three inner layers but were present in appreciable quantity in layer four. A considerable amount of soil adhered to layer four. Layers one and three contained ferrous hydroxide as a black crystalline substance in large amounts and the other layers, two and four, contained a considerable quantity of red ferric hydroxide. There appeared to be an additional layer of ferric oxide or hydroxide between the pipe metal and layer one of the sample. The sample parted at a weak boundary between the innermost layer of the ferrous material and the layer of ferric material next to the pipe.

26. A sample of the roughened, brittle brass from the screen section of well 19 at Station 106+55 and a control sample from one of the wells which showed no sign of corrosive disintegration were analyzed quantitatively to determine the relative proportions of zinc and copper in the corroded and uncorroded material. This analysis was made for the purpose of verifying the conclusion drawn from the rough brittle condition of the corroded brass as to the nature of the corrosion. The evidence of roughness and brittleness indicated a process of selective corrosion known as dezincification in which chemical attack on the brass causes the zinc and copper to go into solution. The copper is redeposited from solution as a spongy amorphous mass of metal at the site of the corrosion and the zinc remains in solution and is carried off. The control sample from an apparently uncorroded well screen, which was only slightly discolored, showed a typical yellow brass color when scrubbed with a stiff brush and was ductile. No analysis of the brass used in the well screens was available; however it was thought likely that it was common yellow brass in which the nominal content of zinc and copper are 34 per cent and 66 per cent, respectively. This conclusion was verified by analysis of the control specimen, which gave 65.79 per cent copper and 33.83 per cent zinc. The remainder, 0.38 per cent, is probably impurities. Analysis of the specimen from well 19 gave 65.50 per cent copper and 30.68 per cent zinc. The 3.82 per cent remainder is thought to be due to fine soil particles which were trapped in the porous mass of redeposited copper and could not be removed by washing or brushing. The loss of zinc verifies the assumption of the dezincification process.

PART III: DISCUSSION OF RESULTS

The Nature of Corrosion

27. The results of the chemical analyses of both the effluent water and the corrosion products from the drainage wells and the other evidences of corrosion described previously indicate by their variability the complexity of the corrosion process at Sardis Dam. Interpretation of the results of corrosion studies is seldom a clear-cut procedure. Hence, before discussing the significance of the observations and analyses presented, it is considered pertinent to review briefly the nature of corrosion, possible and likely corrosion processes and some of the more important factors which influence those processes.

28. Corrosion may be defined in general as the electrochemical processes by which an environment causes deterioration of the materials comprising a structure. Corrosion takes various forms for different materials, although it is most often considered with reference to the partial or complete destruction of metal structures. The metals used in the fabrication of useful items, whether pure or alloyed are in a crystalline state which is not fundamentally stable. The degree of chemical instability varies widely, but for the more common industrial metals there is a very strong tendency to form the more stable oxides and salts. This is particularly true of many of the ferrous metals and of copper and many of its alloys. In dry atmospheres, and in the case of certain alloys, oxidation occurring over the entire surface of the metal forms a protective film which inhibits further progress of the reaction and the metal is said to be passive. However, in a moist atmosphere or in water containing

dissolved oxygen, the reaction proceeds by conversion of the oxides to hydroxides and soluble salts which, if dissolved or eroded, expose fresh metal to attack and a continuation of the destructive removal of the metal or destruction of the strength producing crystalline structure.

29. Corrosion of metals in the presence of water is generally an electrochemical process in which the water, due to its normal electrolytic content, acts as a conductor for the transmission of electricity between the cathodic oxide-covered areas and the anodic areas usually formed by discontinuities in the protective oxide cover. Differences in electric potential of as much as 2 or 3 volts may exist between anodic and cathodic areas on metal surfaces. In the case of iron, some of the metal goes into solution in the anodic area as iron or ferrous ions which combine with negative ions in the water, such as the hydroxyls, to form ferrous hydroxide. The negative charge, induced in the metal as a result of formation of the positive ferrous ion at the anode, travels to the cathode where it neutralizes a hydrogen ion in the electrolyte to form gaseous atomic hydrogen. The presence of oxygen in the water causes a further reaction by converting the ferrous hydroxide to either ferrous or ferric oxide which, if deposited over the anode area, may tend to passivate the metal.

30. Numerous factors, other than those mentioned in the very simple case just described, control the corrosivity of an environment. Dissolved salts in the water adjacent to a corroding area furnish acidic and basic ions which react with the primary corrosion products and control the continuation of the process. Dissolved gases, such as carbon dioxide and hydrogen sulfide, form acids in solution which promote corrosion. Alkalinity, particularly of the hydroxide type, retards corrosion. Calcium

carbonate deposits inhibit corrosion, but the presence of carbon dioxide in solution removes this protective coating by forming soluble bicarbonates.

31. The presence of soil in the corrosion environment also affects the process radically. In dry, well-aerated soils, the initial corrosion is rapid, but protective coatings form early in the process and are not destroyed, so that the rate of attack is slowed considerably. In poorly aerated soils, and particularly in soils below the water table, corrosion processes generally continue at a moderate rate, and under some conditions may be accelerated by destruction of the protective coatings formed initially. There is a general tendency for corrosion of metals in soils to be concentrated in local anodic areas and to progress by the formation of pits which eventually perforate the material. Pitting may occur in an atmospheric or subaqueous environment as well as in soils, but it is more characteristic of the latter. This characteristic concentration of the process is due to the restriction imposed by the nature of the soil on the electrochemical processes and to such effects as rupture of protective oxide coatings by localized stresses from soil grains. Soluble salts leached from the soils and variations in the soil permeability control corrosion processes within the soil.

32. The presence of two or more different metals in contact within a structure and in contact with an electrolytic environment leads to galvanic corrosion of one of the metals. Metals exhibit certain electrical potentials with respect to each other as a consequence of which they are either anodic or cathodic in their mutual reactions. The potential differences may amount to several volts; for example, iron is anodic

(negative) to copper by about 1 volt but is cathodic (positive) to zinc by 0.3 volts, to aluminum by 1.2 volts and to magnesium by nearly 2 volts. When two metals are in contact, as in the case of a brass well screen attached to an iron riser pipe, and in contact with an electrolyte, such as the pore water in soil, a galvanic cell is established in which the iron pipe is the anode and the flow of electric current through the electrolyte removes metal from the iron pipe without damage to the brass screen cathode. The rate at which this type of corrosion takes place depends on the contact potential difference of the metals, the conductivity of the electrolyte and on the formation of inhibiting layers on the anode and cathode.

33. Corrosion of metals by anaerobic bacteria is another factor which is of importance under certain conditions. In addition to the absence of oxygen which, as the name implies, is a necessary condition for their life process, growth of these bacteria depends on the presence of moisture, proper alkalinity or environmental pH, organic matter and specific nutrient salts. One of the current theories of the action of certain species of these bacteria in corrosion processes is that they make use of sulfates in the water to oxidize the cathodic hydrogen normally present over areas of iron in contact with water. The sulfates are reduced to hydrogen sulfide in this process and the reaction proceeds to the formation of ferrous sulfide. Depolarization of the cathodic areas of the iron by removal of the hydrogen enhances the galvanic activity between the anodic and cathodic areas and causes an accelerated corrosion rate.

34. The effects of specific chemical characteristics of an

environment on corrosion processes cannot be considered individually, but must be treated as closely related within the entire chemical reaction and subject to influence of external factors such as the rate of flow of water in the vicinity of the corrosion process. Among the more important chemical factors to be considered in studying a corrosive environment are the pH value, the total acidity, total alkalinity and the base- and acid-radicals included in the electrolyte. The pH value is defined as the negative exponent of the concentration of hydrogen ions in solution. A value of 7 represents a neutral solution; values of pH less than 7 indicate acidity, greater than 7 indicate alkalinity. The pH value is therefore indicative of the extent of ionic dissociation which exists in a solution. It is not a measure of the total acidity or of the total alkalinity, since weak acids or weak bases are only partially dissociated in solution. Only the dissociated acids, bases, or salts take part in the electrolytic reactions involved in corrosion processes. Hence the pH value is in some degree a measure of the rate at which the corrosion reaction will progress, the more rapid reactions occurring for the lower, more acid pH values. The total acidity and total alkalinity values, on the other hand, indicate the total amount of the chemical radicals of these types present in solution whether dissociated or not. These values give some indication of the continuity of the corrosion process, since they are a measure of the quantity of corrosive or inhibitive agents available to replace that portion of the dissociated ions which is lost as a result of corrosion. The rate of flow of the electrolyte, which is controlled by soil permeability as well as by hydraulic head, also affects the rate of the corrosion process by replenishing locally the supply of

electrolyte and removing soluble corrosion products and in the case of high rates of flow by eroding the less soluble incrustations. It is evident that these factors operate in an intricate pattern to affect the corrosion process. Other factors, such as the presence of dissolved gases, the types of acids, and the presence of galvanic couples, also have interrelated influences on the process and must be taken into account in interpreting the results of a corrosion analysis.

Analysis of Corrosion Data

35. It is evident, from the photographs of typical wells from the original system shown in plate 8, that the corrosion processes which took place on these wells varied widely along the length of the system. At the south end, the brass screens were vigorously attacked, showing signs of dezincification, and the galvanized wrought-iron riser pipes had been subject to only mild corrosion. At the north end, the brass well screens showed essentially no damage from corrosion, but the riser pipes were disintegrated, in some cases beyond recovery. The central portion of the system was subject to varied attack but neither the screens nor riser pipes of the wells in this vicinity were damaged to the serious degree found near the extremities of the system. These differences in corrosion attack were not evident in the wells of the experimental system, since it was situated near the southern end of the original system and was of limited lateral extent.

36. The data from the chemical analyses of the water presented in table 2 and particularly those from the Waterways Experiment Station analyses show a similar variation over the length of the well system.

These data show a definite difference between the water from wells south of well 74 at Station 93 and that from wells north of well 86 at Station 89+80. In the remainder of this report, this division will be referred to as distinguishing the south and north parts of the original well system, although the division is evidently not sharp, and both of the sections defined include part of the central portion of the system referred to in the preceding paragraph. The data from the analyses performed by the Barrow-Agee laboratories do not give much evidence to support this division because only one sample, that from well 86, was taken from a well of the northern part of the system, and that well is really within the central group and is a borderline case. The distinctive differences in both corrosion attack and corrosive environment at different parts of the well system must be related and the relationships should point toward the major causes of corrosion in either case.

37. The pH values for all samples of water from the Sardis wells reported in table 2 were acid. The lake water samples were very slightly acid with one exception which, with a pH of 7.8, was definitely alkaline. The distinction between characteristics of the effluent from the northern and southern portions of the well system is evident in their average pH values. The average pH value for the water from wells tested between 1 and 73 was 5.8 and for the water from wells tested between 86 and 116 was 6.3. Water from the toe-drain lateral discharge pipes was in general less acid than that from the wells, but more acid than the lake water. This would indicate that the acidity of the effluent is derived principally from the soil through which it passes. Evidently the water from the wells, which had traversed the longer path within the soil and may have

been in direct contact with the lignitic clay, had taken a greater quantity of soluble acidic material into solution.

38. The total acidities determined in the Waterways Experiment Station analyses indicate a general differentiation between north and south portions of the well system, but contrary to that indicated by the pH values. The well water from the southern part of the system shows in most cases lower total acidity than that from either the north portion wells or the toe-drain laterals. Only sulfuric and carbonic acids were found by the Waterways Experiment Station analysis to be present in the water from the wells, although the Barrow-Agee analyses showed some chlorides and silicates to be present therein. The distinction between the water samples from wells of the northern and southern portions of the system as shown by the pH values and total acidities, suggests that in the southern samples, where the pH was somewhat more acid although the total acidities were lower, a predominance of strong, highly dissociated inorganic acids exists. Conversely, the less acid pH values and higher total acidities of the samples from the northern wells indicate the probable predominance of organic, weakly-dissociated acids.

39. The water analyses showed complete absence of hydroxyl alkalinity and indicated the presence of carbonate alkalinity in only one of the Barrow-Agee well samples. However, the bicarbonate alkalinity was found to be appreciable in all of the Waterways Experiment Station analyses (it was not identified in Barrow-Agee tests) and was roughly four times greater in the water from the wells of the north portion of the system than in that of the southern wells. The bicarbonate radical is usually indicative of the presence of carbonic acid. Hence, if that acid

is present in considerable concentration, the alkaline character of the bicarbonate radical might be expected to give a less acid pH value than the total acidity tests would indicate. This, in fact, may account in part for the reversal noted between the pH-acidity and total acidity for the different portions of the well system. Carbonic acid is formed by reaction of water with carbon dioxide. Hence, water which has passed through a soil in which carbon dioxide is being evolved by organic oxidation may contain the gas as a constituent of carbonic acid and in solution. The tests for free carbon dioxide which were included in the Barrow-Agee analyses may thus be considered to bear a somewhat indirect relationship to the bicarbonate alkalinity tests of the Waterways Experiment Station analyses. The condition of the Waterways Experiment Station water samples at the time of testing precluded the determination of free carbon dioxide in them. It is notable that the free carbon dioxide found in the one borderline northern well, well 86, was nearly twice that found in the four wells of the southern part of the system which were tested by the Barrow-Agee Laboratories. These facts, combined with the very low free carbon dioxide content of the lake water samples, indicate that very appreciable quantities of carbon dioxide gas must have been available for reaction and absorption within soils traversed by the water effluent from the northern part of the drainage system. This condition existed in a much lesser degree in the vicinity of the southern part of the well system.

40. Water hardness was determined by the soap method in both analyses. It is related to the calcium and magnesium content of the water, but is neither very exact nor particularly significant to the corrosion processes involved in the well system. The hardness shows a distinct

increase of several fold from the lower values of the water from the southern wells to the higher ones found for water from the northern wells. The tests for calcium and magnesium content showed comparable increases in the well water from the north end of the system over that from the south end.

41. The test for iron and aluminum as undifferentiated R_2O_3 oxides gave rather unexpected results for the samples from the wells of the southern part of the system, where not a trace of either was found. However, these metals were found to be present in the samples from the wells of the northern portion of the system, and particularly from the extreme north end wells where corrosion of the riser pipes was very severe. It is possible that delays in testing the samples may have made it impracticable to recover all of the iron and aluminum by normal methods in some of the analyses. This condition seems likely in view of the high iron content of the lignitic clays as shown by the Rock Island District analysis and general reports of the taste and iron-staining qualities of the water from wells of the south end of the system.

42. Of the three inorganic acid radicals for which tests were made, only the sulfate tests gave significant results. Neither chlorides nor silicates were found in the Waterways Experiment Station analysis of the well water, although moderate quantities of silicates were identified in the toe-drain lateral outlet samples. The Barrow-Agee analyses showed moderate quantities of all three acid radicals except for one composite sample made up from toe-drain outlet specimens in which the sulfate concentration was found to be 68 ppm. The sulfate content was found to be appreciably more for the samples from wells of the northern group in the

Waterways Experiment Station tests than for those from the southern group. Wells in the vicinity of those the water from which showed only a trace of sulfate (wells 29, 44 and 58), were subjected to only mild corrosion. Water from the wells of the northern part of the system contained a greater concentration of sulfates than that from the southern wells, although the relative difference was not so great as the total acidity values might suggest it should be. The analysis of the lignitic clay specimen performed by the Rock Island District laboratory in 1940 indicates that a copious amount of sulfate was present. Although the method of analysis, leaching in boiling distilled water, undoubtedly exaggerated the conditions as they would be represented by normal ground-water leaching, nevertheless considerable sulfate concentrations should be expected in the ground water near the lignitic clay deposits. The iron-aluminum analysis for the same clay sample suggests that these materials should also be found in large amounts in the ground water near the clay masses. The very high sulfate (260.3 ppm) and high iron-aluminum (86.4 ppm) contents of the water sample from the toe-drain lateral outlet at Station 90 suggest that this water comes directly from the vicinity of part of the lignitic clay mass. The results of both the total acidity and pH tests show very acid conditions and the bicarbonate alkalinity concentration is abnormally low for the water at this site. This corroborates the evidence of the sulfate and iron-aluminum tests.

43. There were, unfortunately, no facilities available at the time the water analyses were made for the performance of dissolved gas tests. Knowledge of the concentration of dissolved oxygen, carbon dioxide, and hydrogen sulfide would undoubtedly aid materially in understanding certain

of the apparently paradoxical results shown by the analysis, such as the coincidence of low pH acidity and high total acidity in the northern part of the well system and the generally low sulfate content throughout the well system. The absence of the dissolved carbon dioxide data is compensated to some extent by the bicarbonate alkalinity tests. However, both the dissolved oxygen data, which are indicative of the amount of free oxygen available for corrosion by oxidation, and the dissolved hydrogen sulfide data, which are indicative of the activity of anaerobic bacteria in reducing sulfates, would be very helpful aids in assigning proper corrosion processes in the interpretation of chemical analyses. The effects of the presence of oxygen and carbon dioxide in the fluid environment of corroding metal has been described briefly at the beginning of this part of the report. The probable significance of the presence of hydrogen sulfide has also been indicated in the discussion of bacterial corrosion.

44. Recent evidence based on water samples taken in 1948 and observations made at that time tends to clarify the situation concerning the dissolved gas content of the water. During sampling operations, it was noted that effluent water from the vicinity of Station 80, which corresponds approximately to the north end of the original well system, had a rusty brown color with traces of oily scum. A thick foamy layer formed on the water wherever obstructions slowed its flow. The upper surface of this layer had a typical ferric, red color; however, beneath this surface the layer consisted of a black material similar to ferrous sulfide. The latter changed to a substance of typical ferric color immediately upon exposure to the atmosphere. The water samples, taken directly from the wells and sealed without exposure to the atmosphere, formed a fine black

deposit on the underside of the bottle cover upon standing for several days. This deposit vanished immediately upon exposure to air. It is considered possible that this deposit was ferrous sulfide which was converted to soluble ferric sulfite or sulfate by oxidation. These facts strongly suggest the presence of considerable amounts of hydrogen or ferrous sulfide in the water from the present wells in the vicinity of the north end of the original system, and as a corollary, the absence of dissolved oxygen in the water. The latter deduction was corroborated by dissolved oxygen analyses made at the site on water samples from wells in the vicinity of both Station 80 (north end of the original well system) and Station 110 (south end of the original system). These analyses showed no evidence of dissolved oxygen from the vicinity of Station 80 and concentrations of the order of 50 ppm of dissolved oxygen from the vicinity of Station 110. In the absence of definite data concerning the presence of these two factors in the samples taken from the original well system and in view of other evidence that the water is essentially similar in the samples taken in 1948, it is considered reasonable to assume that the water from the north end of the original system contained little or no dissolved oxygen and relatively abundant sulfides, and that the water from the south end contained a copious supply of dissolved oxygen.

45. The soil profile, shown schematically in plate 1, shows that north of Station 90 a massive lignitic clay formation underlies the well system, while southward, except for a few lenses of the clay, the sand extends more than 100 ft below the wells. The lignitic clay was found to be rich in sulfates and in organic matter, which is a potential source of carbon dioxide. Both of these chemicals, which are important to certain

corrosion processes, were found in higher concentration in the water from the wells of the northern part of the system over the massive clay deposit than from that of the southern wells. It seems also likely, although no data are available to support the premise, that the formation of carbon dioxide from the lignitic clay should rob the water of much or all of its free or dissolved oxygen. A similar distribution of calcium in the water samples from the wells -- greater in the north portion than in the south portion of the system -- and its occurrence in considerable quantity in the clay, strengthen the argument for consideration of the lignitic clay as the source of the more aggressive of the corrosion agents in the water.

Corrosion processes

46. It is possible to deduce from the knowledge of conditions derived from the foundation soil profile, the water analyses and the visual and chemical analyses of the corroded wells, and from known environmental requirements of certain corrosion processes, certain facts which indicate the probable major corrosive reactions and processes which were responsible for the destruction of the wells of the Sardis Dam toe-drain system. Near the southern extremity of the system, the brass well screens were subject to dezincification; the galvanized iron riser pipes were subject to only very mild attack. Water from these wells contained moderate quantities of strong acids and relatively low amounts of carbonic acid and was in general not very corrosive. The foundation soil was such as to furnish only minor quantities of sulfate and carbon dioxide, since lignitic clays occur only in scattered lenses beneath the southern portion of the well system. This water may, however, have contained appreciable

quantities of dissolved oxygen. Within the central portion of the well system, corrosion of the well screens and of the riser pipes occurred but was not serious. In this region the water shows strong acidity, although the sulfate content is lower and the carbonic acid concentration, as represented by the bicarbonate alkalinity, is increased. The foundation is similar to that under the extreme south end of the system, with a possible decrease in the lignitic clay lenses close to the wells. The experimental well system was situated in the indefinite transition region between the extreme south end of the well system and the central portion. The corrosion of the metallic wells of this group was mostly of a galvanic nature and the disintegration of the porous and perforated concrete was typical of sulfate attack on that material. The wells of the north end of the main well system suffered destructive corrosion in the galvanized iron riser pipes only, the brass well screens being essentially uncorroded. The water from these wells contained relatively large amounts of carbonic acid and considerably more sulfates than that of the remainder of the wells. There is also evidence to support the assumption of considerable amounts of hydrogen sulfide and of complete absence of dissolved oxygen in the water from these wells.

47. It is difficult to account for the very considerable difference in the corrosive attack on the brass well points at different positions along the length of the well system. However, although authorities report somewhat conflicting views on the environmental requirements for dezincification of brass, it seems to be agreed that a slightly acid electrolyte with appreciable quantities of free oxygen and some carbon dioxide tends to aggravate the attack by this process. These conditions appear to be

satisfied at the south end of the well system. Just what the controlling factor is which differentiates the environment of the south end of the system from the central portion and causes no appreciable dezincification in the latter region, is not clear from the data available either in this study or in the literature. It is noteworthy also that in the southern part of the well system galvanic corrosion at the brass-iron pipe junction seems to be of a minor nature, possibly because the zinc furnished to the electrolyte by the dezincification process tends to inhibit removal of the zinc coating of the galvanized iron pipe.

48. It has been noted that the wells of the central part of the system were not badly damaged by corrosion, although some attack was evident on all wells. In this part of the system, the most serious damage appeared to be that which affected the brass screen sections at the riser pipe coupling, as illustrated in plate 6. This corrosion was evidently localized to the vicinity of the coupling threads and was probably due to high stresses caused by jamming the screen over the sharp threads and was probably enhanced by some galvanic corrosion.

49. Corrosion of the galvanized wrought-iron riser pipes of the wells of the northern part of the system was extremely severe. The attack varied from general deep pitting over the whole exterior of the pipe to concentrated attack several feet above the joint with the screen section and several feet below the concrete ditch lining. In all cases the interior of the riser pipes showed evidence of uniform corrosion. The extent of the attack varied from general heavy incrustation to general perforation and disintegration. In one case, well 99, disintegration was so complete that no trace of the riser pipe could be found in a carefully

hand-augered hole 4 ft deep. The water from this part of the well system, although not so acid in terms of the pH value, contained more sulfates and bicarbonate or carbonic acid than that of the southern section. This water also gave evidence of hydrogen sulfide. In view of the evidence available, it seems reasonable to assume that anaerobic bacterial corrosion was the primary form of attack. The high bicarbonate alkalinity of the water indicates a large concentration of carbon dioxide which, if formed from the organic content of the lignitic clay, would remove the dissolved oxygen from the water and make it a habitable environment for the particular type of bacteria required by the process suggested. Likewise, the sulfate derived from the lignitic clay furnishes another of the environmental requirements of these bacteria which reduce the sulfates to sulfides. This process would account for the occurrence of only moderate sulfate concentrations where much higher concentrations might be expected because of the proximity of the lignitic clay. It also accounts for the evidence of sulfides noted in the water surface scum and in the deposits beneath the tops of the sample bottles. The life process of the sulfate-reducing anaerobic bacteria involves oxidation of the hydrogen which forms a polarizing sheath over the cathodic areas of the corroding iron with the oxygen derived from the sulfate-reduction process. This removal of the polarizing hydrogen increases the potential (reduces the hydrogen overvoltage) between the cathodic and anodic areas of the iron surface and aggravates the corrosive attack. The fact that this process occurs in soil increases the tendency to localization of the corroding anodic areas and intensifies the rate of penetration of the anodic pits.

Summary of corrosion processes

50. The corrosion processes which were deduced to be active in the destruction of the wells of the original toe-drain system at Sardis Dam may be summarized with their causes as follows: Lignitic clay, underlying the southern and central parts of the well system in minor lenticular masses and occurring as a massive deposit beneath the northern part of the system, served as a source of varying concentrations of sulfates and carbon dioxide in the water which passed through the wells. In the portion of the system above the lesser clay deposits, the sulfate and carbon dioxide derivatives were in relatively low concentration, and dissolved oxygen was probably plentiful. In this environment, either the brass well screens were subject to selective corrosion known as dezincification as in the southern portion of the system, or general mild corrosion occurred at both the brass screens and the galvanized iron riser pipes as in the central portion. Conversely, in that portion of the well system above the massive lignitic clay deposit, the water was virulently corrosive. The carbon dioxide or its derivatives and sulfates were present in strong concentration. The existence of considerable organic matter in the clay and of large amounts of carbon dioxide in the water suggests the absence of free oxygen in the water due to the formation of the carbon dioxide. This condition and the copious supply of sulfates provided an adequate environment for sulfate-reducing anaerobic bacteria. The life process of these bacteria is such that corrosive pitting of iron would be intensified and the corrosion would proceed at an extremely rapid rate.

51. A secondary corrosion process which was undoubtedly active in some degree in all of the wells of the original system is galvanic

corrosion. Since all of the wells consisted of brass screens coupled to galvanized iron riser pipes, the presence of an electrolytic fluid in the soil or within the well would be expected to form a galvanic cell in which the brass well screen would be the cathode. This condition would result in more or less rapid corrosion of the anodic iron pipe in the vicinity of the coupling. This type of corrosion is evident to some extent in the wells of the central portion of the system and undoubtedly added appreciably to the destruction of the riser pipes in the northern part of the system. The absence of any marked galvanic corrosion in the wells of the southern part where the brass was dezincified is not readily explainable but may be connected in some way with the interaction of that corrosion process in the brass and the zinc coating on the galvanized riser pipes.

52. Corrosion of the metal wells of the experimental system was probably due entirely to either dezincification, in the case of the brass-screen wells, or to galvanic corrosion in the case of the well screens formed of iron pipe cores wrapped with brass or bronze screens or rods. The three sheet metal wells of this system were so thin that only mild corrosion might be required to render them useless in a short time.

53. The destruction of the nonmetallic well points of the experimental system was limited to the concrete pipe screens. In these cases, it is likely that the sulfates and bicarbonates in the water attacked the cement and weakened it so that the binder was leached from the aggregate of the porous concrete. The cement-asbestos pipe showed only very minor evidence of such attack and the perforated concrete was of sufficient thickness and imperviousness that the attack was limited to the outer

surface of the pipe, exposing the aggregate as shown in the photograph of plate 7. Neither the chemically inert glazed clay pipe nor the cypress well point showed evidence of damaging attack by the water, except as the metal riser pipes and coupling parts were corroded.

PART IV: CONCLUSIONS

54. The conclusions derived from analysis of the data obtained in this study are:

- a. The only adequate materials for use in drainage wells at Sardis Dam are those which are chemically inert in the subsurface environment. Of the numerous materials and types of well points used in the two well systems described in this report, only two -- the perforated cypress wood and the perforated vitreous clay pipe -- were undamaged. However, it is likely that the cement-asbestos pipe might also be classed as relatively permanent and suitable for use in a well system, provided a method of perforation which would prevent the formation of weak zones were used in the well point, and dependable non-corrosive couplings were used with a riser pipe of similar material.
- b. There is a direct relationship between the position of the lignitic clay deposits in the foundation, the chemical nature of the effluent water and the corrosion processes which acted on the wells of the two systems. Proximity of the lignitic clay increased the vigorousness of the corrosive attack.
- c. The most effective corrosive agents in the effluent well water determined by chemical analysis were the sulfates and carbon dioxide derivatives which were leached from the lignitic clay.
- d. The effective corrosive agents which were deduced from other evidence than the water analysis were the probable variation in dissolved oxygen in the drainage system water, and the sulfate-reducing anaerobic bacteria in the sub-soil at the north end of the well system.
- e. The major corrosion process which affected the galvanized wrought-iron riser pipes was probably due to the agency of anaerobic bacteria.
- f. The major corrosion process which affected the brass well screens was dezincification which was found in the southern portion of the well system.
- g. There is evidence of galvanic corrosion in the vicinity of the coupling between the brass well screens and iron riser pipes in the wells of the original system. This process was probably the major cause of corrosion in the bimetallic

well screens of the experimental system in which brass screen or rod was wrapped on perforated iron cores.

- h. Soil corrosion was shown to be effective in the destructive pitting of the riser pipes and exercised a strong influence in concentrating the effects of the postulated bacterial corrosion of the riser pipes.
- i. The results of the various parts of this study and the difficulties involved in the analyses of those results indicate the advisability of a comprehensive program of chemical and physical analyses of the possible corrosive environments which are included in a project site. The analysis should be made well in advance of construction in order that full advantage of the knowledge derived from it may be taken in selecting materials and protective devices to insure optimum useful life for all structural parts which will be subject to the corrosive environments.

TABLES

Table 1

EXPERIMENTAL WELL SYSTEM

Well No.	Type of Wellpoint	Well Screen Diameter in.	Openings			Screen Elevation		Riser Pipe	
			Slot Width in.	Wire Mesh per in.	Hole Diameter in.	ft msl		Diameter in.	Length ft
						Top	Bottom		
1	Perforated iron pipe	3.0	0.050	--	---	192.9	190.9	2.5	28.6
2	wrapped with trape-	2.0	0.010	--	---	200.8	190.8	2.0	20.8
3	zoidal brass wire	2.5	0.020	--	---	192.1	190.1	2.0	29.6
4	Perforated iron pipe wrapped with fine & coarse brass screen	2.0	-----	28	---	192.8	190.8	2.0	28.9
5	Perforated brass	2.0	-----	40	5/32	200.1	190.3	1.5	21.5
6	sleeve over brass	2.0	-----	40	5/32	192.7	190.7	1.5	29.3
7	screen	1.5	-----	50	1/8	192.3	190.3	1.5	29.3
8	Slotted brass tube	2.5	0.008	--	---	200.4	190.3	2.0	21.2
9		1.75	0.012	--	---	192.7	190.7	1.5	28.9
10		1.75	0.012	--	---	192.5	190.5	1.5	29.1
11		1.75	0.012	--	---	200.7	190.7	1.5	20.9
12		2.5	0.012	--	---	200.2	190.2	2.0	21.3
13		2.5	0.012	--	---	192.4	190.4	2.0	29.0
14		2.5	0.025	--	---	192.8	190.8	2.0	28.8
15		2.5	0.050	--	---	192.6	190.7	2.0	28.9
16		2.5	0.012	--	---	192.7	190.7	2.0	28.8
17		2.5	0.025	--	---	192.7	190.2	2.0	28.8
18		2.5	0.030	--	---	192.4	190.4	2.0	29.1
19	Brass screen on perforated iron core	1.25	-----	40	1/8	192.1	190.1	1.25	29.5
20	Slotted brass tube	1.5	0.008	--	---	199.4	190.7	1.5	22.2
21		1.5	0.008	--	---	200.8	190.7	1.5	20.7
22		2.5	0.008	--	---	192.8	190.7	2.0	28.7
23		2.5	0.008	--	---	201.0	190.9	2.0	20.6
24		2.5	0.008	--	---	192.8	190.7	2.0	28.7
25	Perforated iron pipe wrapped with fine & coarse brass screen	2.0	-----	8+28	---	192.5	190.5	2.0	29.0
26		2.0	-----	8+30 x 40	---	199.7	190.8	2.0	21.8
27		3.0	-----	14	---	192.7	190.8	2.0	28.7
28		1.5	0.010	--	---	200.8	190.8	2.0	20.7
29		2.0	0.010	--	---	199.6	190.7	2.0	21.7
30		1.5	0.010	--	---	199.5	190.7	2.0	22.0
31		3.0	-----	14+28	---	192.9	190.8	2.0	28.6
32	Perforated brass tube on brass screen on corrugated brass liner	3.0	-----	28	1/16	192.8	190.7	2.0	28.8
33	Slotted brass tube	2.5	0.008	--	---	200.7	190.7	2.0	20.9
34		2.5	0.100	--	---	192.8	190.8	2.0	28.8
35	Perforated brass sleeve on brass screen	2.25	-----	--	5/32	192.8	190.8	2.0	28.8
36	Perforated cement-	2.0	-----	--	1/8	192.9	190.8	2.0	28.6
37	asbestos tube	2.5	-----	--	1/8	201.2	191.2	2.5	19.7
38	Porous concrete	6.0	-----	--	---	200.9	190.9	3.0	20.4
39	Perforated cypress wood	2.5	-----	--	1/4	202.5	192.5	2.0	19.0
40	Perforated iron pipe liner in porous cement fine gravel covered with screen	2.5	-----	--	---	201.0	191.0	2.0	20.5
41	Porous concrete	4.0	-----	--	---	200.7	190.7	3.0	20.7
42	Perforated concrete pipe	4.0	-----	--	1/4	200.4	190.4	3.0	21.0
43	Perforated vitreous clay pipe	6.0	-----	--	5/8	200.8	190.8	3.0	20.6
44	Perforated 10-in. steel casing filled with sand & gravel filter	10.0	-----	--	3/16	200.8	190.8	10(gravel)	20.1
45	Perforated 10-in. casing with gravel packed around a 2-in. perforated core	10.0	-----	--	3/16+1/8	200.8	190.8	3.0	20.6
46	No. 20 gauge galvanized sheet steel, perforated	2.5	-----	--	3/16	210.9	205.9	2.5	10.6
47		2.5	-----	--	3/16	211.0	201.0	2.5	10.7
48		2.5	-----	--	3/16	209.9	189.9	2.5	11.9

Table 2

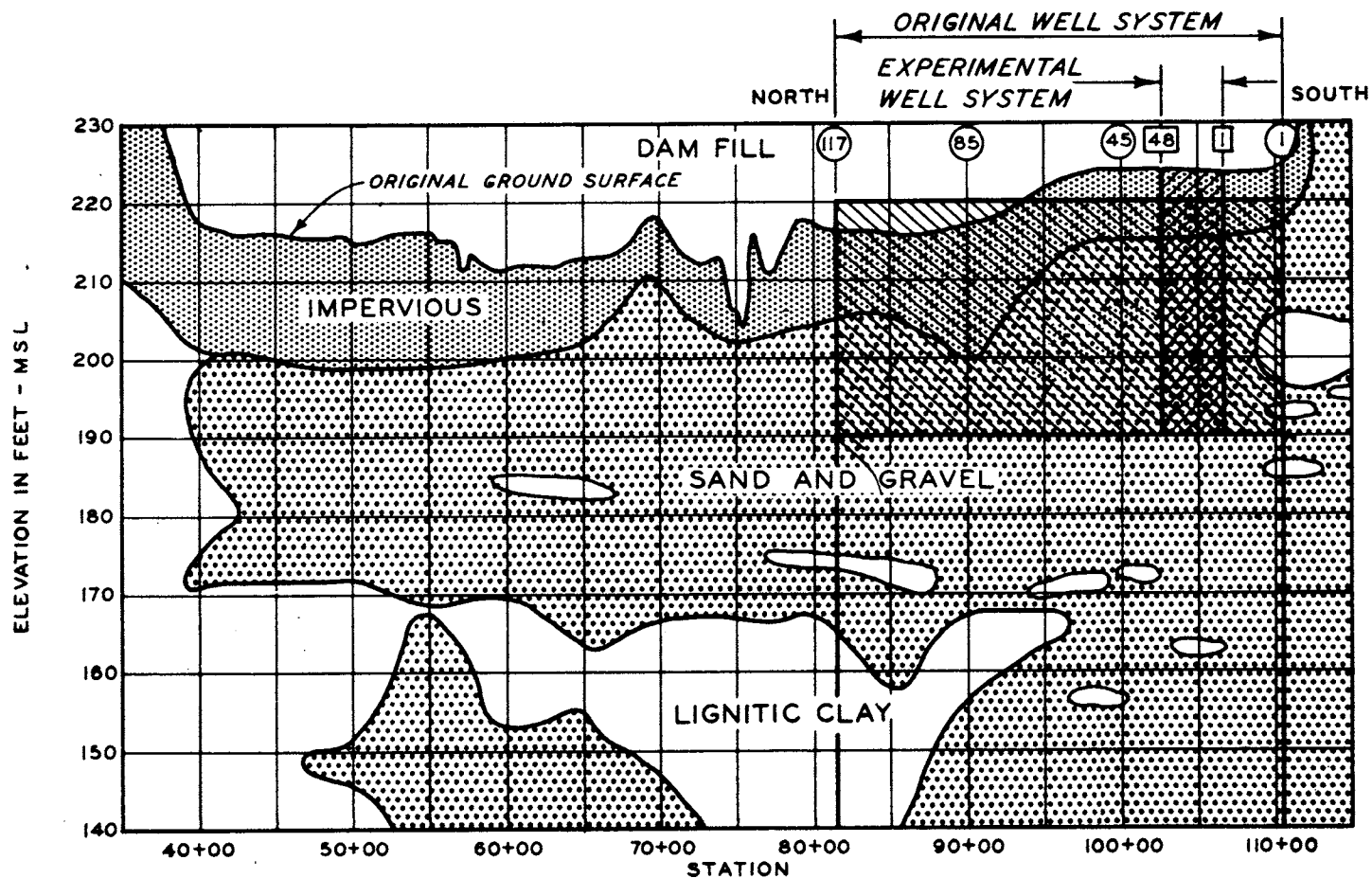
RESULTS OF WATER ANALYSES

No.	Location	Station	pH	Total Acidity ppm	Total Alkalinity ppm			Free CO ₂ ppm	Fe & Al as R ₂ O ₃ ppm	Ca ppm	Mg ppm	SO ₄ ppm	Cl ppm	SiO ₂ ppm	Dissolved Solids ppm	Hardness Soap Method ppm
					HCO ₃ * ppm	OH	CO ₃									
Clay from spillway**		-----	2.70	----	---	---	---	--	1000.0	230.0	----	2100.0	0.0	160.0	-----	---
W-1	Well 1	111+00	5.85	9.0	16	0.0	0.0	--	0.0	4.1	0.6	11.5	0.0	0.0	64.0	60
W-2	Well 15	107+55	5.95	6.0	15	0.0	0.0	--	0.0	3.5	0.5	3.5	0.0	0.0	48.0	28
W-3	Well 29	104+05	6.50	5.0	18	0.0	0.0	--	0.0	2.4	0.5	Trace	0.0	0.0	40.0	21
W-4	Well 44	100+30	5.75	15.0	22	0.0	0.0	--	0.0	2.9	0.5	Trace	0.0	0.0	30.0	32
W-5	Well 58	96+80	5.80	3.0	22	0.0	0.0	--	0.0	3.4	0.5	Trace	0.0	0.0	42.0	48
W-6	Well 59	96+55	5.80	4.0	24	0.0	0.0	--	0.0	3.5	0.5	6.4	0.0	0.0	40.0	44
W-7	Well 73	93+05	5.80	24.0	32	0.0	0.0	--	0.0	6.6	1.2	7.6	0.0	0.0	53.0	52
W-8	Well 87	89+55	6.15	21.0	79	0.0	0.0	--	3.6	16.6	3.9	15.8	0.0	0.0	124.0	143
W-9	Well 88	89+30	6.20	33.0	82	0.0	0.0	--	3.2	17.6	4.0	12.3	0.0	0.0	129.0	156
W-10	Well 102	85+79	6.30	24.0	81	0.0	0.0	--	4.2	16.9	4.0	5.6	0.0	0.0	99.0	130
W-11	Well 115	82+50	6.45	15.0	115	0.0	0.0	--	20.4	26.7	3.6	18.3	0.0	0.0	177.0	156
W-12	Well 116	82+25	6.50	11.0	142	0.0	0.0	--	53.2	32.0	3.4	10.7	0.0	0.0	164.0	166
W-13	Piezometer J-1	-----	6.45	28.0	45	0.0	0.0	--	3.0	5.3	0.0	0.0	0.0	12.0	53.0	60
W-14	Toe Drain Lateral	102+00	6.10	22.0	87	0.0	0.0	--	6.2	13.2	5.4	67.7	0.0	18.0	158.0	91
W-15	Toe Drain Lateral	90+00	4.45	72.0	10	0.0	0.0	--	86.4	36.0	11.3	260.3	0.0	21.2	467.0	268
W-16	Toe Drain Lateral	70+00	6.55	43.0	165	0.0	0.0	--	36.0	36.0	13.4	33.3	0.0	21.6	202.0	163
W-17	Toe Drain Lateral	54+00	6.40	27.0	87	0.0	0.0	--	6.8	17.9	6.0	38.2	0.0	17.0	184.0	107
W-18	Toe Drain Lateral	42+00	6.35	18.0	72	0.0	0.0	--	9.8	14.2	2.8	29.8	0.0	4.2	146.0	64
BA-1	Lake Water	-----	7.80	----	---	---	21	Trace	20.3	4.3	4.7	6.2	2.0	35.0	16.0	---
BA-2	Well 5	110+05	5.40	----	---	---	18	39	4.0	3.7	1.5	8.9	2.1	12.7	43.0	---
BA-3	Well 9	109+05	5.30	----	---	---	---	30	----	----	----	----	---	----	----	11
BA-4	Well 21	106+05	5.60	----	---	---	---	31	----	----	----	----	---	----	----	17
BA-5	Well 37	102+05	5.90	----	---	---	---	32	----	----	----	----	---	----	----	16
BA-6	Well 86	89+80	6.00	----	---	---	---	52	----	----	----	----	---	----	----	72
BA-7	Toe Drain Lateral	106+00	6.10	----	---	---	---	31	----	----	----	----	---	----	----	53
BA-8	Toe Drain Lateral	102+00	5.90	----	---	---	---	34	----	----	----	----	---	----	----	64
BA-9	Toe Drain Lateral	90+00	5.70	----	---	---	---	44	----	----	----	----	---	----	----	160
BA-10	Toe Drain Lateral	86+00	6.20	----	---	---	---	40	----	----	----	----	---	----	----	146
BA-11	Composite BA-3-6	-----	----	----	---	---	---	--	Trace	8.8	7.2	7.2	3.4	13.8	25.0	---
BA-12	Composite BA-7-10	-----	----	----	---	---	---	--	1.6	31.0	27.5	68.0	11.3	11.0	27.0	---
BA-13	Bottom of Lake	-----	6.90	----	---	---	---	5	2.2	6.4	3.3	4.5	3.4	8.2	67.2	---
BA-14	Bottom of Lake	-----	6.70	----	---	---	---	7	3.4	8.8	7.0	3.4	4.4	10.2	95.8	---
BA-15	Top of Lake	-----	6.90	----	---	---	---	5	3.4	8.4	2.6	3.1	3.9	6.0	72.6	---
BA-16	Top of Lake	-----	6.00	----	---	---	---	5	2.0	9.0	3.7	4.1	3.9	7.2	67.6	---

* Total alkalinity was entirely bicarbonate and is expressed as ppm of CaHCO₃.

** Analysis of filtrate after leaching lignitic clay sample in hot distilled water. Reported by Rock Island District.

PLATES



LOCATION OF WELLS:

DOWNSTREAM 500 FT TO 570 FT FROM Δ
 STA 111+00 TO STA 82+0
 ORIGINAL WELLS ON 25-FT CENTERS
 EXPERIMENTAL WELLS ON 6.3-FT CENTERS

LEGEND

- (45) WELL NUMBER - ORIGINAL SYSTEM
- [48] WELL NUMBER - EXPERIMENTAL SYSTEM

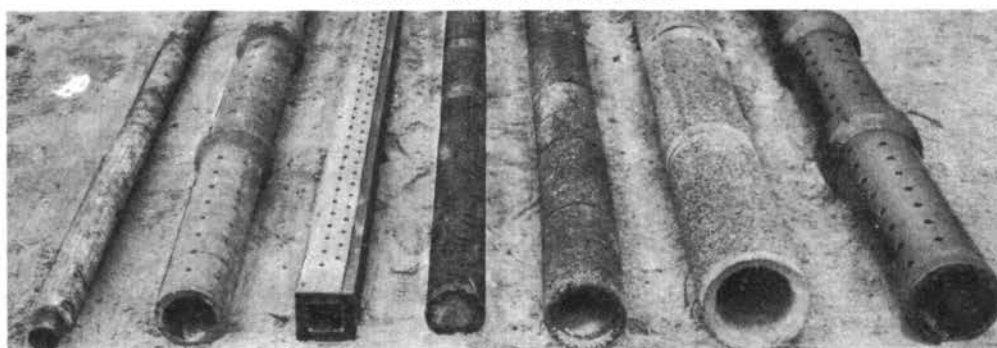
FOUNDATION SOIL PROFILE
 SARDIS DAM

LOCATION OF
 WELL SYSTEMS



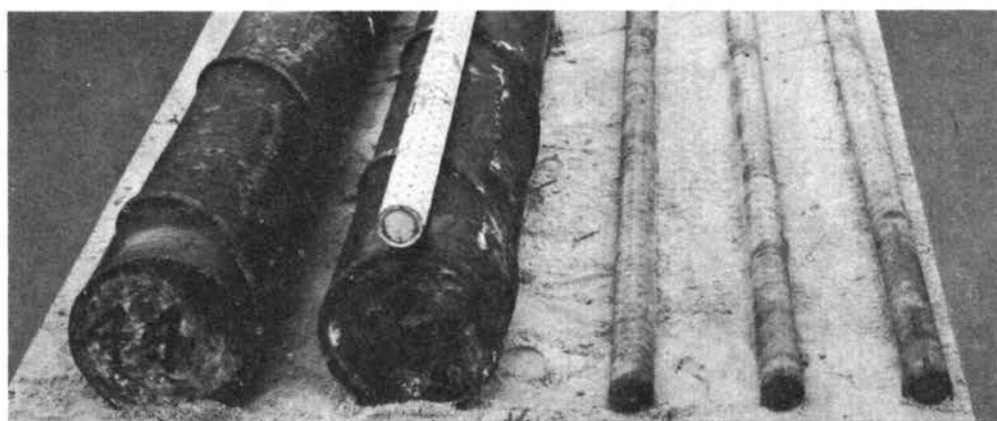
15 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33

BRASS WELL SCREENS



36 42 39 40 41 38 43

NON-METALLIC WELL SCREENS

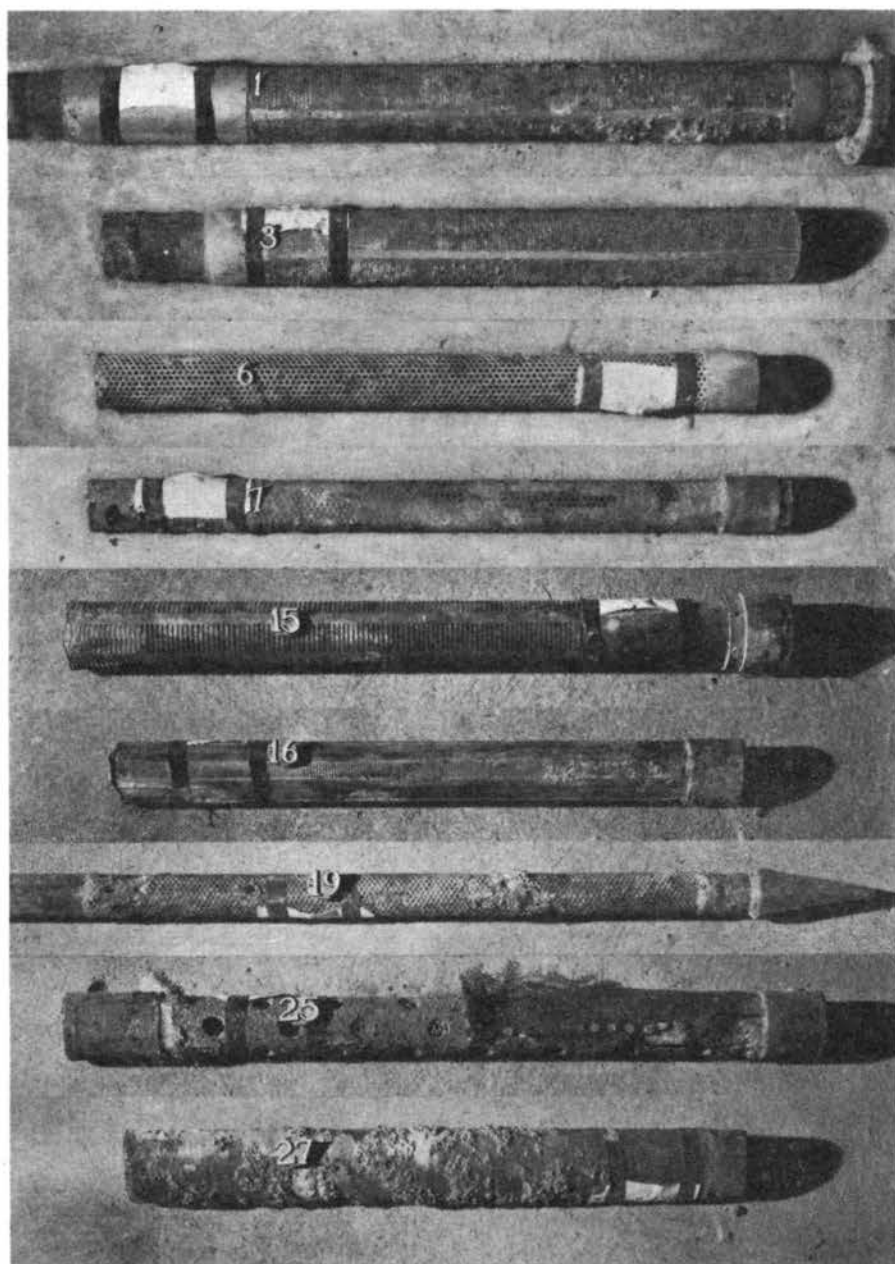


44 45 46 47 48
NONCONNAH TYPE AND PERFORATED SHEET METAL WELL SCREENS

SARDIS DAM EXPERIMENTAL WELL SYSTEM

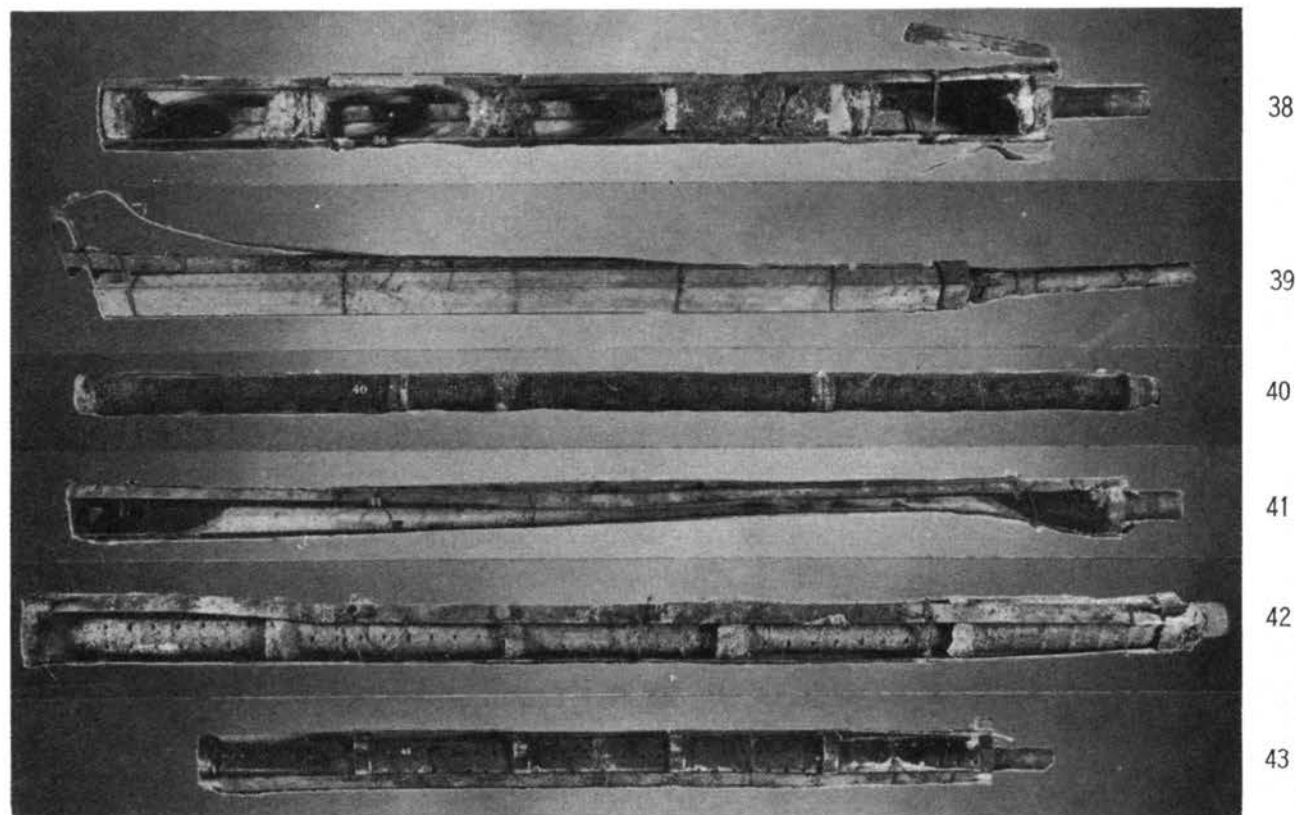
TYPES OF WELL SCREENS

NOTE: SEE TABLE 1 FOR DESCRIPTION OF WELL SCREENS.



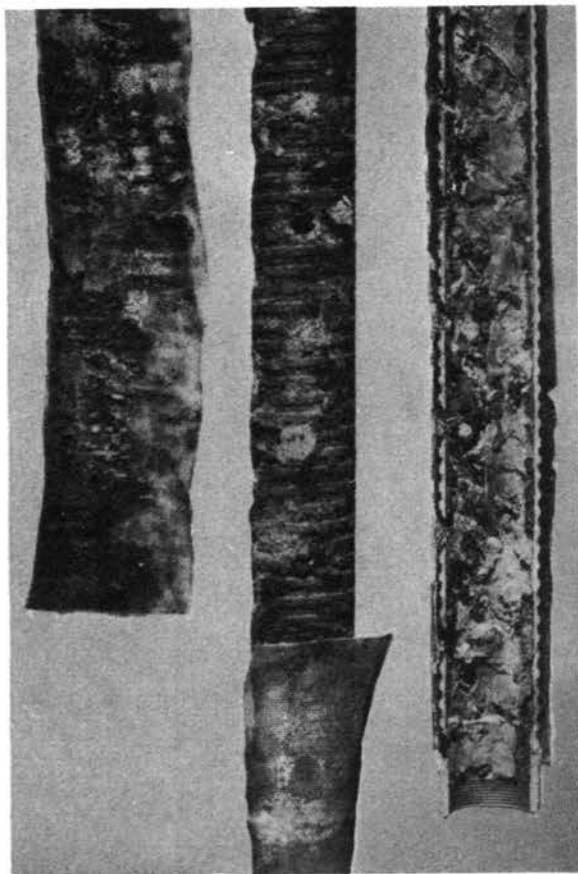
SARDIS DAM EXPERIMENTAL WELL SYSTEM
CORRODED WELL SCREENS

NOTE: NUMBERS IDENTIFY WELL SCREENS IN TABLE I.

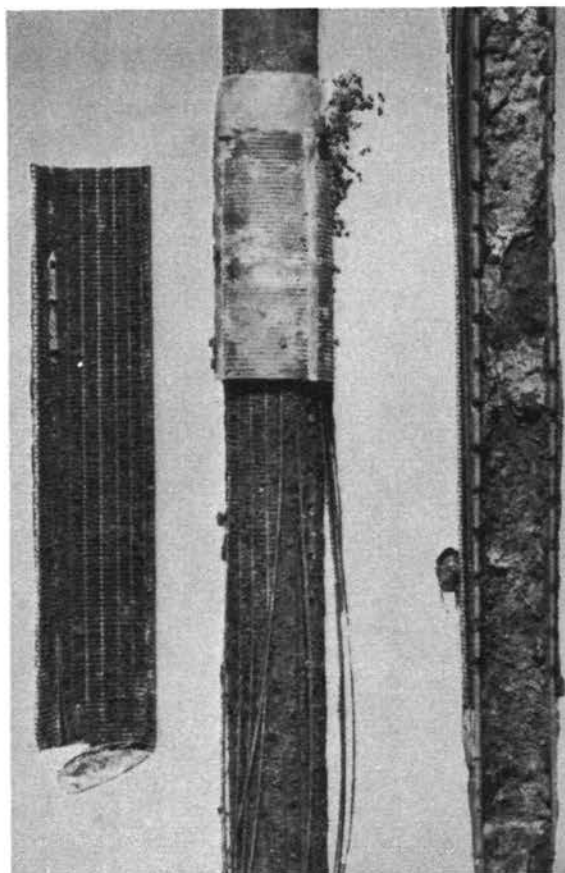


SARDIS DAM EXPERIMENTAL WELL SYSTEM
NON-METALLIC WELL SCREENS AFTER RECOVERY

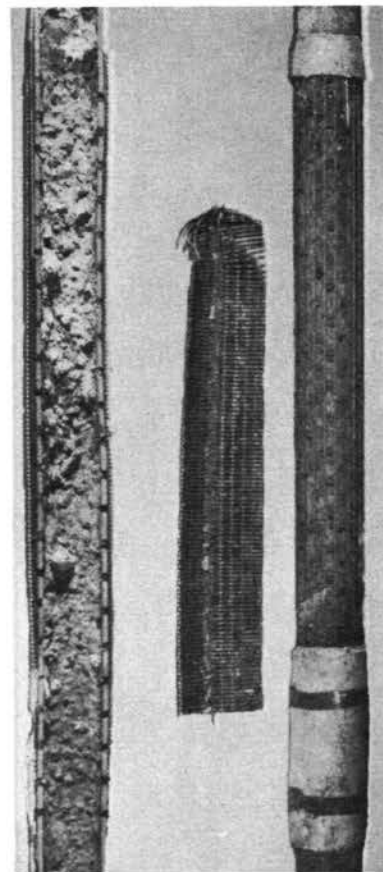
NOTE: NUMBERS IDENTIFY WELL SCREENS IN TABLE 1 AND PLATE 2.



WELL 27



WELL 3

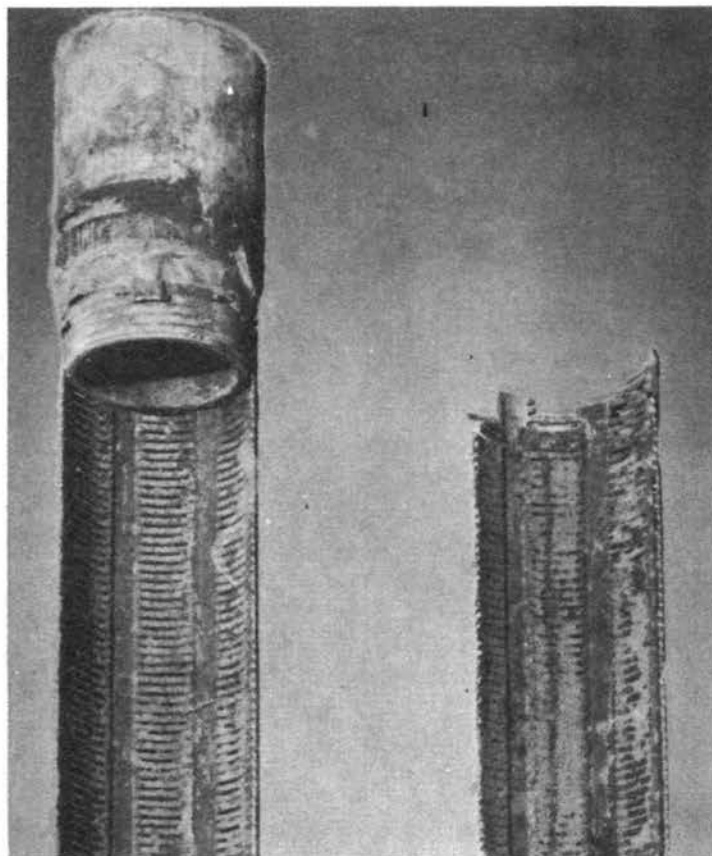


WELL 1

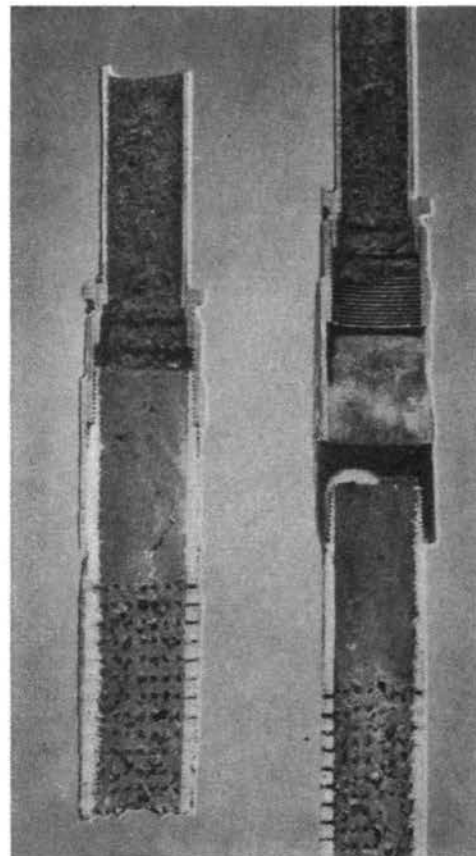
ISARDIS DAM EXPERIMENTAL WELL SYSTEM

DISSECTED CORRODED BIMETALLIC WELL SCREENS

NOTE: NUMBERS IDENTIFY WELL SCREENS IN TABLE I.



WELL 33

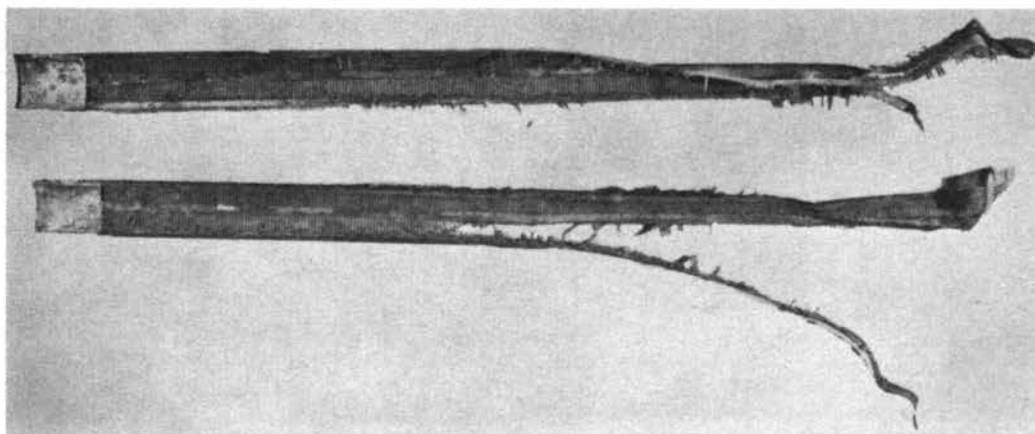


WELL 37

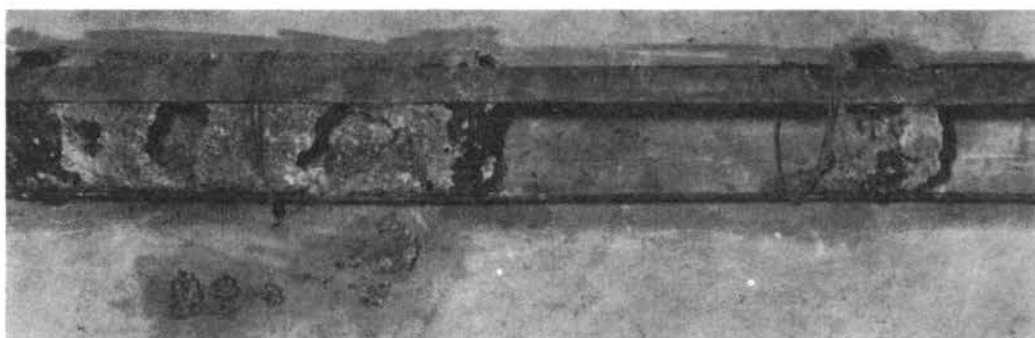
SARDIS DAM EXPERIMENTAL WELL SYSTEM

DISSECTED CORRODED WELL SCREENS

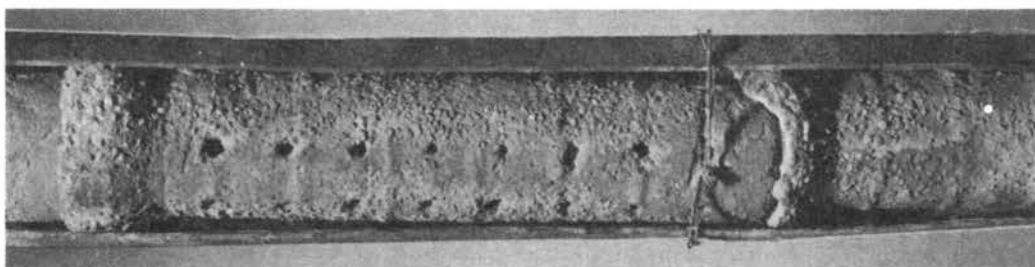
NOTE: NUMBERS IDENTIFY WELL SCREENS IN TABLE I.



WELL 19. DISSECTED SLOTTED BRASS WELL SCREEN



WELL 38. POROUS CONCRETE PIPE WELL SCREEN



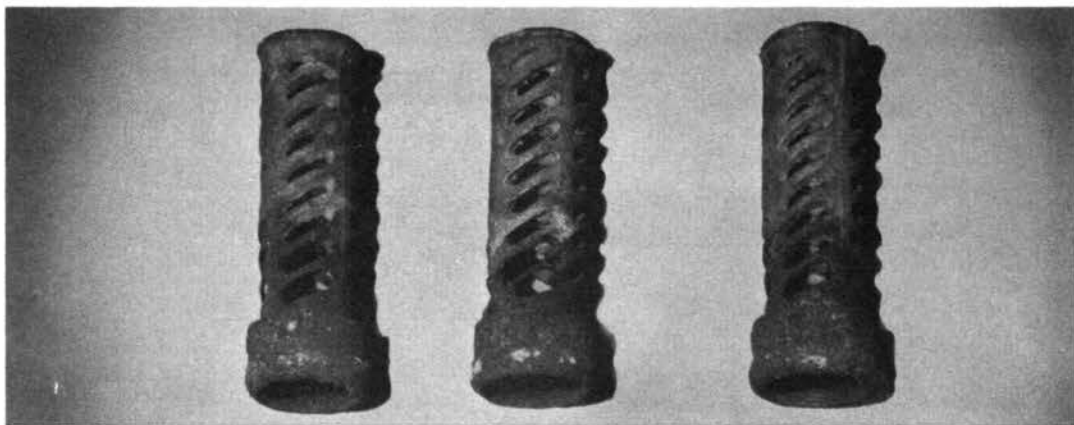
WELL 42. PERFORATED CONCRETE PIPE WELL SCREEN



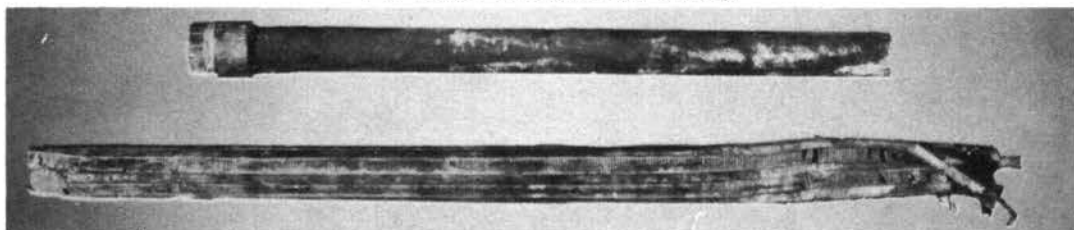
WELL 48. PERFORATED 20-GAGE GALVANIZED
SHEET IRON WELL SCREEN

SARDIS DAM EXPERIMENTAL WELL SYSTEM
DETAILS OF SEVERAL CORRODED WELL SCREENS

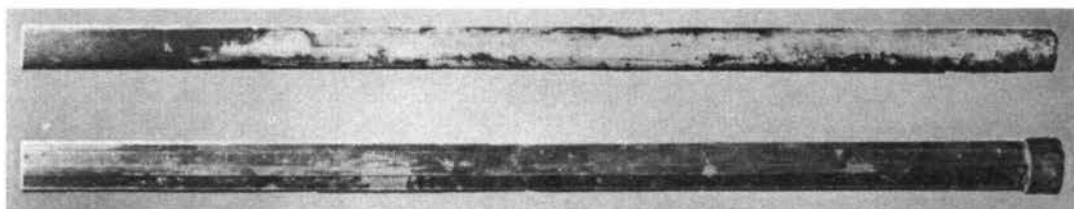
NOTE: NUMBERS IDENTIFY WELL SCREENS IN TABLE 1.



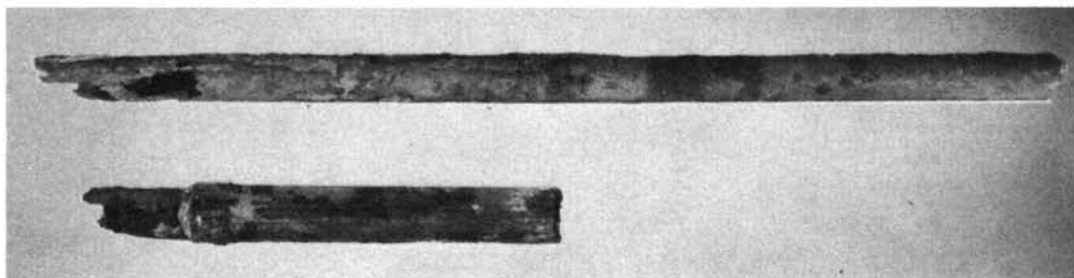
TYPICAL STRAINER CAPS



WELL 3. SOUTH END OF SYSTEM: STATION 110+55



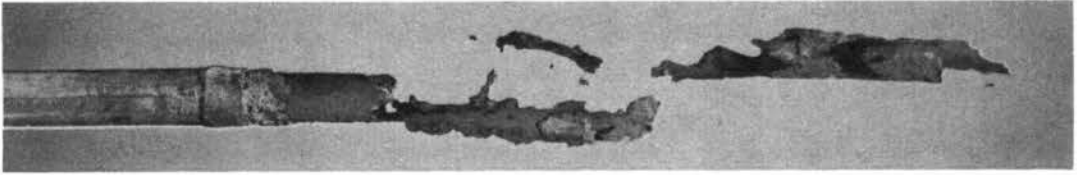
WELL 58. CENTRAL PORTION OF SYSTEM: STATION 96+80



WELL 104. NORTH END OF SYSTEM: STATION 85+27

SARDIS DAM ORIGINAL WELL SYSTEM

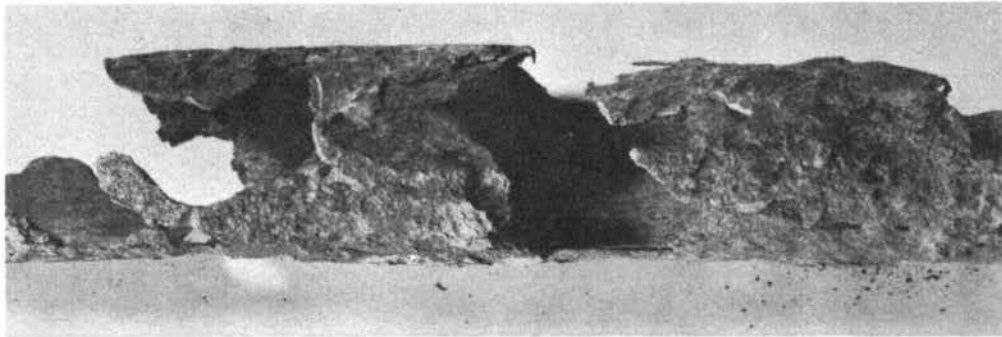
CORRODED WELLS FROM ORIGINAL WELL SYSTEM



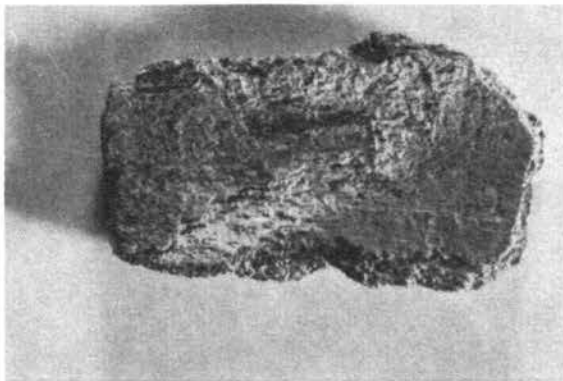
WELL 106 - STATION 84+75. SCREEN AND RISER PIPE



WELL 106. DETAIL OF RISER PIPE CORROSION



WELL 106. DETAIL OF RISER PIPE CORROSION



WELL 104 - STATION 85+27. EXTERIOR INCRUSTATION

SARDIS DAM ORIGINAL WELL SYSTEM

DETAILS OF TYPICAL NORTH END RISER PIPE CORROSION

APPENDIX

APPENDIX

RECOMMENDED ANALYSIS AND PROTECTIVE PROCEDURES

1. It is considered pertinent to the purpose of the foregoing report and to the design of future drainage well or similar installations to suggest the type and scope of studies which should be made in order that the utility and economic worth of such installations may be fully realized. The procedure should follow two lines: the first involves corrosivity tests on which to base choice of materials; the second involves the employment of protective measures where necessary to inhibit the more intractable corrosion processes.

Testing Schedule

2. The value of certain tests, such as water analyses, for discovering the corrosive nature of an environment is fully demonstrated in the report. Similarly, the restrictions imposed on such a study by the absence of certain data, such as the dissolved oxygen content, are evident. The importance of correlation of such test data with other types of information such as the soil profile is also apparent. The complexity of the corrosion process in general is such that the necessity of a thorough investigation of all possible sources cannot be over-emphasized. In outline, the investigation of the site for an installation such as a drainage-well system should include the following:

- a. Soil profile study. This should delineate the various strata and classify the component soils or rocks within which the installation is to be placed and with which the ground water that will reach the system can come in contact.

- b. Water analyses. Water samples should be taken and complete standard water analyses with the addition of analyses for dissolved gases including oxygen, carbon dioxide, and hydrogen sulfide should be made. The sampling program need not be detailed, but sufficient samples at several critical depths at various points along an extensive system should be taken to give a comprehensive picture. Samples should be taken with proper equipment and by a skilled technician and should definitely not be mixed into composites if full value is to be derived from the analyses.
- c. Soil samples. Samples of the soils to be encountered by the system or by the water flowing into the system should be taken, leached in distilled water, and the water analyzed as described above. If feasible, it might be better to perform these soil analyses first and reduce the water analysis program along lines indicated by the results of the soil analyses.
- d. Soil corrosivity tests. Samples of the soils with which the system is to come in contact should be taken and Denison corrosivity tests* should be made to determine their relative corrosivity and possibly to indicate the thickness and type of metal to be used. If time permits, it is recommended that several sets of metal coupons be buried in pertinent locations in triplicate or greater numbers, and the samples be removed for measurements at intervals over a period of several years.

Protection Procedures

3. Protective measures may be adopted in most cases where corrosivity of the environment or material requirements make them necessary. These measures may involve protective coatings where nonmetallic wells are concerned and either protective coatings or cathodic protection for metal wells. The first of these involves any of various paint, enamel, plastic bitumen or plated or sprayed metal coatings and in some cases

* The Denison soil corrosivity test consists of an accelerated corrosion test in a soil cell. Periodic measurements of the galvanic current produced by the cell provide a means for determining the corrosive characteristics of the soil for the electrode metals used in the cell.

neat Portland cement. The type and ingredients of the coating will be determined by the corrosive environment and material to be protected. In general, protective coatings must be applied before installation of a system. It is probable that the use of bituminous enamel protective coatings on the exterior of the riser pipes of the Sardis Dam drainage wells might have increased the useful life of many of the wells.

4. Cathodic protection consists of inhibiting corrosion of metal by maintaining the protected metal cathodic with respect to a non-essential piece of metal. Previous descriptions in the report of the electrolytic process involved in corrosion have shown that the destructive corrosion occurs at anodic areas. If the entire structure which is to be protected is maintained at a potential with respect to another nonessential piece of metal such that the protected structure is everywhere cathodic to the other metal, then the latter will be anodic and subject to corrosion while the structure remains uncorroded. Various methods are employed for achieving this type of protection. In the externally powered methods, the anode usually consists of a buried mass of steel such as rails or pipe to which a protected steel structure is connected electrically through a low-voltage d.c. power source with properly applied polarity. Power sources which are commonly used for this type of protection include rectified power from nearby a.c. lines, and generators driven by either gas engines or windmills. A different method of attaining cathodic protection employs the natural potential difference between the two metals of a galvanic couple to furnish the requisite power and polarity. Proper choice of the metal to be used as a sacrificial anode for protection of a structure achieves this purpose

without an external power source. Sacrificial anodes used for protection of iron or steel consist of either zinc, aluminum, or magnesium. These anodes are buried near the protected structure and connected electrically to it with a heavy insulated cable or bus. This type of protection is not limited to soil corrosion use, but may be used in water and to protect the interior of metallic tanks or other vessels.